Catena 163 (2018) 321–331

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Modelling the impact of land use changes on peak discharge in the Urseren Valley, Central Swiss Alps

Mathias Fercher[a], Matthias H. Mueller[b,c], Abdallah Alaoui[d,*]

[a] Aarefeldstrasse 19A, 3600 Thun, Switzerland
[b] Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland
[c] Applied and Environmental Geology, University of Basel, Bernoullistrasse 32, 4056 Basel, Switzerland
[d] Centre for Development and Environment (CDE), University of Bern, Hallerstrasse 10, 2012 Bern, Switzerland

ARTICLE INFO

Keywords:
Central Alps
Land use changes
Green alder
Shrubs
Return period
Peak discharge

ABSTRACT

In alpine regions, global climate change will likely alter rain and snowfall patterns and increase the frequency of extreme meteorological events such as floods. These events, combined with land use changes, may pose an immediate hazard to the life and properties of downslope inhabitants and to water resource structures downstream. The aim of this study is to evaluate the impact of land use changes (e.g., areas covered by grassland, green alder, and dwarf shrubs) on peak discharge for different return periods and different scenarios (past, current, and future) in the Urseren Valley in the Central Swiss Alps. In addition to the entire Urseren Valley, we also considered four microcatchments of various sizes and land covers within the valley. We used the ZEMOKOST model, which considers the impact of a wide range of vegetation and channel characteristics on surface hydrology. Results at the catchment scale show an increase in peak discharge for all return periods from 2 to 300 years. In two microcatchments, simulation results indicate that expected changes in the vegetation cover will drastically decrease peak discharge in the future for all return periods, by up to 41% (for a 100-year return period). At the catchment scale, although the surface area covered by green alder increases by 38% and the area covered by dwarf shrubs decreases by 26% from the current to the future scenario, the peak discharge increases for all return periods except for the 2- and 5-year return periods. It appears that the drastic decrease of grassland area from the current to future (− 52%) scenario is responsible for the slight increase in peak discharge (about 4% for a 100-year period). In addition, surface area covered by dwarf shrub not only decreases from the current to future scenario, but also clusters into more continuous zones damping lateral flow and resulting in such moderate increase. The consistency between observed and simulated peak discharge for a 100-year return period attests the reliability of our modelling outcomes. Careful land use planning taking into account the results of our analysis can help to better manage land and water resources in the region.

1. Introduction

Mountainous headwater catchments play an important role for water supply (e.g., drinking water production) to the adjacent lowlands (e.g., Finger et al., 2013; Rice and Hornberger, 1998; Viviroli et al., 2011). In alpine catchments, meteorological, glaciological, periglacial, and hydrological phenomena display very intimate and complex interactions that affect process variability at both small and large spatial and temporal scales (Verbunt et al., 2003). Changes in the global climate will likely alter rain and snowfall patterns and cause an increase in the frequency of extreme meteorological events, such as floods (e.g., Beniston et al., 2011; Birsan et al., 2005; Gobiet et al., 2014). The estimation of extreme floods is crucial to sustainable water resource system management since extreme events may pose an immediate hazard to the life and properties of downstream inhabitants and water resource structures.

The expansion of shrubs is a phenomenon occurring worldwide (Sala and Maestre, 2014; Tape et al., 2006). Shrubs of different types are for example expanding in arctic tundra environments due to climatic changes (Tape et al., 2006). The forested area in Switzerland increased by 1304 km^2, including 174 km^2 shrub woodland, between the observations in 1983/85 and 2009/11 (WSL, 2012, cited in Caviezel et al., 2017). Almost all of the newly forested area (97.5%) lies within the Swiss Alpine region (Brändli, 2010). In the Swiss Alps, green alder (*Alnus viridis (Chaix) DC*), an early successional species, is a major component of the increasing subalpine shrub woodland: 70% of the

* Corresponding author.
E-mail address: abdallah.alaoui@cde.unibe.ch (A. Alaoui).

https://doi.org/10.1016/j.catena.2017.12.032
Received 23 August 2017; Received in revised form 21 December 2017; Accepted 25 December 2017
Available online 03 January 2018

shrub areas consist of green alder, 20% of dwarf mountain pine (*Pinus mugo* subsp. *prostrata*), while the remaining 10% is dominated by hazel (*Corylus avellana*) and various willow species (*Salix sp.*) (Brändli, 2010).

In the Urseren Valley in the Central Swiss Alps, the influence of shrub encroachment on the total water balance (Alaoui et al., 2014) as well as mean water transit times and geochemistry at baseflow conditions (i.e. in the long term) was shown to be of minor importance (Mueller et al., 2013). However, shrub encroachment might affect the generation of surface runoff, since the vegetation cover strongly interacts with runoff components during rainfall events (Bachmair and Weiler, 2011). In the case of the Urseren Valley, it has led to higher soil hydraulic conductivities (Alaoui et al., 2014) and a higher infiltration capacity of the soil (Caviezel et al., 2014), which in turn might decrease surface runoff generation. The dominant land use type in the Alps is grassland, and its degradation is mostly due to the coupled processes of soil erosion and excess surface runoff. Accordingly, information on the magnitude of peak discharge in response to extreme events can help to better manage soil and water resources in the region. The question is: How will a certain specific change in land use affect the hydrology at the catchment scale?

To assess the impact of land use and land cover changes on environmental processes, including surface hydrology, different scenarios have to be implemented in global and regional models of climate change and land-ecological systems. Therefore, modelling studies contributing to a better understanding of interactions in the human–land system (Hovius, 1998) and of the hydrological dynamics in catchments (Huismann et al., 2009) are still at the focus of attention (Rogger et al., 2017).

While the potential effects of changes in land use and climate on freshwater resources and runoff behavior in Urseren Valley catchments were assessed from a long-term perspective (e.g., Alaoui et al., 2014), the literature offers no information about their short-term impacts on surface runoff generation so far. This study aimed to fill this gap by evaluating the impact of land use change, expressed as the expansion of green alder, on peak discharge for different return periods in the Urseren Valley, Switzerland.

2. Material and methods

2.1. Location and geology of the study area

The catchment of the Urseren Valley is located in the Central Swiss Alps (Fig. 1) and covers an area of 191 km^2. The Urseren Valley is a glacially influenced U-shaped valley with steep, rugged slopes and a flat valley bottom, running from west to east. In terms of elevation, the catchment extends from 1400 m a.s.l. at the valley bottom up to almost 3200 m a.s.l. at the highest peaks in the north-west. The southern mountain ridge, the Saint-Gotthard Massif, consists mainly of paragneisses and granites; the northern crests are made up of granites, granitoids, gneisses, and migmatites belonging to the Aar system (Labhart, 1977). The Aar and Saint-Gotthard massifs are separated by the so-called Urseren Zone, which is formed by vertically dipping Permocarbonic and Mesozoic layers along a geological fault line. The latter corresponds to the valley axis.

2.2. Hydrology of the study area

The hydrometeorological conditions in the Urseren Valley are characterized by an alpine climate, with precipitation distributed rather evenly throughout the year. In the Swiss Alps, the Ursern Valley is considered a key region because of its rich natural resources, due in part to its high mean annual precipitation of 1900 mm compared to the mean annual precipitation in Switzerland of 1458 mm (for the period 1961 to 1990) (Schädler and Weingartner, 2002). This results in relatively high mean annual discharge, estimated to be 1540 mm with a runoff coefficient of 0.81 (for Switzerland, the mean annual discharge was 991 mm with a runoff coefficient of 0.68 for the same period).

The region's current hydrological regime can be classified as nivo-glacial. Based on average values over the past 100 years, the catchment is snow-covered from 21 November to 30 April, and snowmelt occurs mainly in May and June. The climatic context is complex due to the valley's geographical situation: being open both in the east and west, it is influenced by the southerly foehn wind that brings large amounts of precipitation in summer.

2.3. Soils in the study area

The most widespread soil types in the Urseren Valley are Podsols and Cambisols (Meusburger and Alewell, 2008). Leptosols are common at higher elevations and on steep slopes. Clayey gleyic Cambisols, Histosols, Fluvisols and Gleysols have developed on the valley bottom, on the lower slopes, and on other fairly flat areas. Soil organic carbon contents of up to 34 wt% were observed in places where riparian wetland soils and peat bogs had developed (Schroeder, 2012). Soil pH is between 4 and 5 throughout the Urseren Valley (Lagger, 2012; Mueller et al., 2013).

The texture of most soils in the Urseren Valley can be described as silt loam or sandy loam. Soils are generally high in silt (41 ± 9 wt%) and sand (50 ± 13 wt%) content; the clay fraction plays a minor role (9 ± 5 wt%) (n = 106) (Gysel, 2010; Mueller et al., 2014). Stone fragments of up to 0.3 m length have been observed within several soil profiles in the Urseren Valley (Mueller et al., 2014). Skeleton content in the soils ranged from 1 to 45% dry weight (dw) (n = 100) on a north-facing slope and from 3 to 65% dw (n = 28) on a south-facing slope (Mueller et al., 2014, Konz et al., unpublished data).

2.4. Assessment of land cover and vegetation types

Catchment scale: Vegetation has been altered strongly by centuries of anthropogenic activities such as pasturing (Kägi, 1973). In recent decades, shrubs have been encroaching into formerly open habitats after grazing activities were reduced (Tasser et al., 2005; Wettstein, 1999). Invasion by shrubs, mainly *Alnus viridis (Chaix) DC* (green alder) along with *Sorbus aucuparia* (mountain-ash) and *Salix appendiculata* (large-leaved willow), has been observed on both the north-facing and the south-facing slopes of the Urseren Valley (Kägi, 1973; Küttel, 1990; Wettstein, 1999). The shrub cover in the valley increased by 32% between 1965 and 1994 (Wettstein, 1999) and by 24% between 1994 and 2004 (van den Bergh et al., unpublished data) and is located predominantly on the north-facing slopes. On the south-facing slopes, the vegetation consists of dwarf-shrub communities and diverse herbs and grass species, and has undergone little change (Kägi, 1973; Küttel, 1990).

Green alder grows in humid and nutritious alkaline soils (Oberdorfer, 1994; Ellenberg, 1996) on calcareous, silty or clay material with high soil moisture. The upper limit of the abiotic environment of green alder is situated around 2000 m a.s.l, while its lower limit is below the base limit of the Urseren Valley. In alpine and sub-alpine regions, green alder compete with spruce, larches and other shrubs and stabilizes slopes which are prone to soil erosion and landslides (Aeschimann et al., 2004). Other anthropogenic factors have strongly contributed to the changes in land use in the region of the Urseren Valley. Expansion of agricultural land on the expense of the coniferous forest has favorited the expansion of green alder (Wettstein, 1999). Dwarf shrubs are also the dominant land cover in the region and contain principally rhododendron that exist up to 2000 m a.s.l. (Aeschimann et al., 2004). Their limiting factors, however, are the disturbance by grazing animals and its extensive use as burning material (Kägi, 1973). At elevations above 2000 m a.s.l., blueberries are the most important vegetation constituting the dwarf shrubs. Extensive livestock farming favors the expansion of dwarf shrubs in Central Alps. Coniferous forest was abundant until the middle Ages and disappears

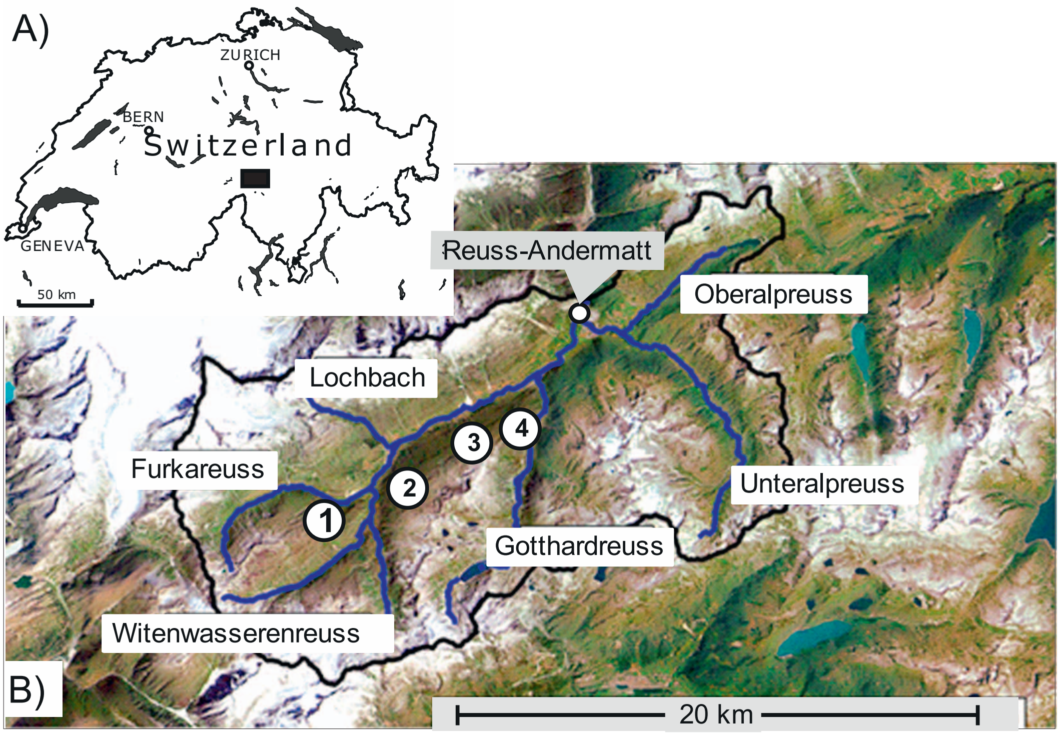

Fig. 1. A) Location of the study area in Switzerland; B) Map of the Urseren Valley catchment showing the main tributaries of the Reuss River and four microcatchments in which basic soil parameters were measured: (1) Laubgädem, (2) Bonegg, (3) Wallenboden, and (4) Chämleten.

due principally to the avalanches and the concurrence of green alder (Maag et al., 2001).

"Traditional agriculture" existing since the middle of 1950s consists principally of grassland. In winter, when the feed stores become weak, the use of pastures for livestock was of great value for the goats especially in slopping grounds. In spring and autumn, the free areas in the mountains serve as pastures and later in autumn, they serve for grazing. This form of agriculture continues to exist today and is expected to persist in some areas in the future.

Microcatchment scale: Four microcatchments were selected to depict changes of land use and their impact on peak discharge under different conditions. The Bonegg catchment is a subcatchment of the Urseren Valley catchment. Bonegg has a surface area of about 0.34 km^2, of which 39% are currently covered by shrubs and 35% by grassland (Fig. 2 and Table 1). In Bonegg, green alder has already occupied its potential niche and very few changes are expected to occur in the future.

The Chämleten is the smallest microcatchment in terms of surface area (0.02 km^2). Although traditional agriculture was dominant in the past, current situation shows that about 80% of the area is covered by green alder due to the rapid changes in the agriculture (Fig. 2). The expansion of green alder is expected to continue in the future to occupy 100% of the total area of the microcatchment.

In Laubgädem (0.11 km^2), extensive livestock farming is widely used and explain the expansion of dwarf shrubs on the expense of grassland from past to current scenario (Fig. 2). As green alder has favorable conditions to grow in this area, it is expected that it will expand further, leaving little room for dwarf shrubs.

Concerning Wallenboden (0.61 km^2), only a third of its surface area is considered as niche of green alder vegetation. About a third of its area located principally in the higher part is covered by grassland and dwarf shrubs (Fig. 2). Under these conditions, it is expected that the expansion of green alder will be limited in the future. Wallenboden and Bonegg microcatchments have comparable land use conditions in terms of topography and vegetation resulting in comparable scenarios projected for the future.

In this study, the past scenario refers to traditional land use observed in the 1950s, characterized by intensive agriculture. Most areas located on sloping ground that were used for agriculture in the past are now covered by shrubs (Kägi, 1973). The future scenario established in

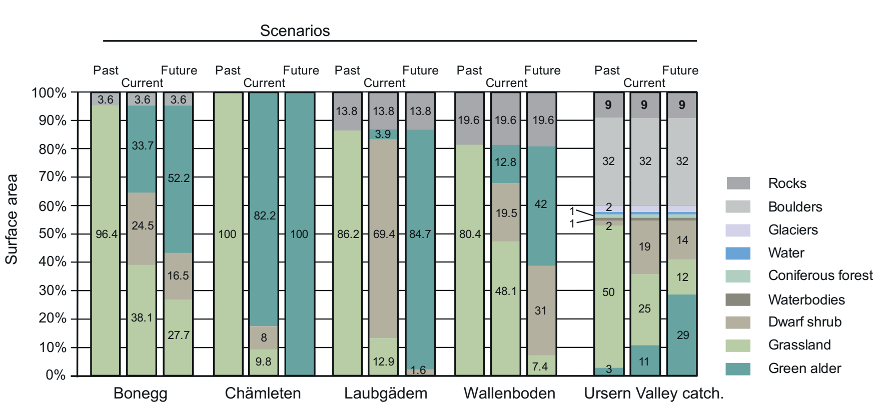

Fig. 2. Shares of land cover types in the scenarios applied in the ZEMOKOST model for the 4 microcatchments and the Urseren Valley catchment.

Table 1
Characteristics (mean values) of the Urseren Valley catchment and the microcatchments.

	Urseren Valley	Bonegg	Chämleten	Laubgädem	Wallenboden
Projected area (km^2)	191.2	0.34	0.02	0.11	0.61
Vegetation cover (%)	56	96	100	86	80
Grassland (%)	25	35	10	13	7
Dwarf shrubs (e.g. *Caluna vulgaris*) (%)	19	23	8	69	31
Bare rocks (%)	41	3	0	14	20
Forest (%)	1	0.1	0	0	0
Shrub cover (mainly *Alnus viridis (Chaix) DC* and *Sorbus aucuparia*) (%)	11	39	82	4	42
Elevation range (m a.s.l.)	1440 – 3200	1551 – 2492	1680 – 1815	1730 – 2285	1500 – 2358
Mean elevation (m a.s.l.)	1400 – 3600	2026	1740	1836	2082
Mean catchment slope (°)	31.5	28	24	20	20

this study is based on an extrapolation of the changes observed over the last fifty years (Fig. 2).

2.5. ZEMOKOST model

2.5.1. Model description

The ZEMOKOST model is an event-based rainfall runoff model commonly used for design flood estimation in small alpine catchments in Tyrol, Austria. In this approach, a design storm with a certain return period is chosen from the rainfall intensity-duration-frequency (IDF) curve indicated in the Austrian standard design tables (Weilguni, 2009) and used as an input to the event model. The duration of the storm is varied, and the storm that results in the largest flood peak is considered to be the representative storm.

The ZEMOKOST model was used because it includes additional options, to consider interactions between dwarf shrubs and green alder and their competitiveness in expanding their niches. The surface runoff processes were estimated in the field by the rule-based method of Markart et al. (2004). The knowledge of common plants in the Alps allowed a good characterization of the runoff situation at the site under consideration. In this approach vegetation, soil characteristics and land use information are used as indicators for the runoff coefficient (*RC)* and retardation coefficients for surface runoff or more specifically overland flow. For the identification of the event runoff coefficient the results of artificial rainfall experiments were used to distinguish seven main hydrologic vegetation/land cover units in the Alps (pioneer vegetation – immature soils; grass vegetation and grassland – meadows; dwarf shrub heaths; bush associations, tall forb associations; forests; and graded and sealed areas). These classes are divided into subclasses which differentiate different types of dwarf or grassland species. The subclasses generally occur under certain typical conditions which are defined by providing complementary information for each subclass such as soil texture (six classes from fine to coarse soil), typical land use forms (e.g. pasturing, skiing), distinct features (e.g. erosion properties) and the predominant soil moisture content. In order to easily identify the predominant soil moisture content in the field the rule-based approach includes a number of indicator plants (Table 2) that hint at different soil moisture conditions from dry to wet. The blueberry is for instance a typical indicator of dry to slightly moist soil conditions, while the king cup only occurs on wet soils.

Table 2 and Fig. 4 give an example of how the rule based approach can be used to identify the runoff coefficients (*RC*) and roughness coefficient (R_g), respectively in the field. First a hydrological vegetation class is identified for the area of interest. R_g characterizes runoff features of the soil surface, comparable with the k-value in the Strickler-equation for the calculation of channel runoff". Using this method, Zeller (1981) describes a parameter in his runtime method, named "water runoff coefficient *c*". This parameter antagonizes slope inclination and flow depth, both increase runoff velocity at the soil surface. The coefficient *c* can be seen as an analogon to Strickler's energy loss coefficient (= roughness coefficient "R_g"), but c is dimensionless. Roughness coefficient is inversely proportional to the concentration time that characterizes the time period from the beginning of the precipitation event to the formation of surface runoff. On the basis of detailed field investigations and existing orthophotos from 2004 (Fercher, 2013), mapping both *RC* and R_g at the microcatchment and catchment scales were obtained for the past and the current situations and projected in the future.

2.5.2. Calibration

The ZEMOKOST model was calibrated based on surface runoff measurements in the field using > 700 artificial rainfall experiments in alpine regions including central Alps (Markart et al., 2004). The artificial rainfall experiments were carried out on different vegetation covers similar to the ones existing in our study region (e.g., green alder, dwarf shrubs) (Fig. 3, and Fig. 4). In the ZEMOKOST model, vegetation, soil characteristics, and land use information are used as indicators for event runoff coefficients (*RC)* and retardation coefficients (c_r) – which serve for estimating the time of concentration on the hillslope according to Zeller (1981) – and for surface runoff or, more specifically, overland flow. *RC* is defined here as the ratio of surface runoff to event rainfall at different rainfall intensities. *RC* was determined based on artificial rainfall experiments with intensities varying between 10 and 120 mm h^{-1}. For rainfall intensities beyond this interval, *RC* values were estimated (Kohl and Markart, 2010).

At the microcatchment scale, the model was calibrated based on measurements of precipitation and discharge during the summers of 2010 and 2011. The highest measured discharges did not exceed 10 mm h^{-1} (Lagger, 2012), thus restricting our calibrations to low discharge values.

More details about the ZEMOKOST model and its calibration can be found in Markart et al. (2004).

2.5.3. Validation

To validate our modelling results, we compared them by means of an independent statistical method that uses Copula functions and overlapping quantile-isolines for the derivation of bivariate design events and is employed by the Federal Office for Environment (FOEN) (DVWK, 2015). In addition, peak discharge measured during August 1987 resulting from a rainfall event corresponding to 100-year period allowed us to validate our modelling peak discharge for this return period.

3. Results

3.1. Modelling results

3.1.1. Bonegg

Modelling results show that for a rainfall event with a 100-year return period, peak discharge decreases by 34% from the past to the current scenario and by 10% from the current to the future scenario (Fig. 5A). The differences are much higher for extreme events (e.g., a

Table 2
Runoff coefficient classes of the dominant land vegetation in the Urseren Valley, 0 < class 1 < 0.10, 0.11 < class 2 < 0.30, 0.31 < class 3 < 0.50, 0.51 < class 4 < 0.75, 0.75 < class 5 < 1, after Markart et al., 2011.

Vegetation unit	Soil	Cultivation/utilization special features	Humidity	Runoff coefficient class
Grassland	Coarse soil, shallow due to reasons of substratum, granular - loose	No grazing	mf-f	3
	Fine soil (rich in skeleton), cohesive, dense	With and without pasturing, dwarf shrub heath up to 25%	mf-f	4
		Grazed/extensified	mf-ff	5
	Very shallow on native rock	Grassland alternates with bare rock dense open talus, steep channels, no-few dwarf shrubs	mf-f	5
Dwarf shrubs (alpenrose & blueberry heath)	Coarse-soil, loose	None	mf-f	0/1
		On small parts damages by livestock (compaction, erosion)	mf-f	2
	Fine-soil, (rich in skeleton)	Matgrass, damages by livestock (compaction, erosion) on max. 25% of the area	mf-f	3
	Fine-soil	Humid, moist - network of small brooks	f-ff	4
		Wet, dense network of small brooks	n Sphagnum	5
Green alder & willow bushes	Coarse soil with fines, loose		f-ff	3–4
	Fine soil	Periodiclly wet, slope water		4
		Slope water, Waserstau, waterlogging, dense network of fine channels	ff-n	5

mf: dry–moderately fresh; f: fresh; ff: very fresh–humid; n: very humid–wet.

100-year return period) than for the minor ones (e.g., a 2-year return period). The decrease in peak discharge from the past to the current scenario is explained by the significant decrease in surface area covered by grassland and the related increase in the surface area covered by green alder leading to a decrease in the surface area of RC_4 (0.51 to 0.75) from 79 to 52% and shift of the roughness coefficient from 0.05 to 0.09 in the major part of the microcatchment (Fig. 6). Similarly, these areas with calculated RC_4 are expected to decrease from 52 to 33% from the current to the future scenario while other areas with smaller RC (RC_2 and RC_3) will increase (Fig. 6A).

The fact that peak discharge differs less between the current and the future scenario than between the past and the current scenario can be explained by the fact that much of the expansion of green alder has already taken place: The observed expansion of green alder between the past and the current scenario amounts to 33.7%, whereas its future expansion is expected to remain below or equal to 18.5%. By contrast, while dwarf shrubs increased by 17% in the past, they are expected to diminish by 5% between the current and the future scenario.

3.1.2. Chämleten

Modelling results show that peak discharge increases from the 2-year to the 300-year return period, while it decreases slightly from the past to the current and from the current to the future scenarios (Fig. 5B). The reason of the small difference between current and future scenarios can be explained by the fact that green alder has already occupied its potential niche and it will cover only very little remaining areas in the future. However, only a small change in peak discharge between the past and the current scenario is recorded (+ 1.5%) despite the drastic changes in land use (reduction in grassland from 100% for the past to 10% in the future). Thiscan be explained by the very short flow pathways to the river within this little microcatchment. These small changes are reflected by the appearance of areas with higher roughness coefficient R_{g5} for the current and future scenarios and disappearance of areas with R_{g3} dominating in the past (Fig. 6B).

3.1.3. Laubgädem

There is a drastic change in the land cover between different scenarios. Peak discharges of the past situation for example are 98 to 443% higher than these of the current scenarios (Fig. 5C). And conversely, they will be 79 to 343% higher in the future than for the current situation. These high differences in the peak discharge between the different scenarios are due to the drastic changes in the vegetation cover. The current situation show that dwarf shrubs cover about 70% of the total area of the microcatchment which generate low surface runoff. Green alder is expected to expand from 4 to 85% accompanied by a decrease in the areas covered by dwarf shrubs from 70 to 1.6% from current to future situation resulting in higher peak discharge (Fig. 2, Fig. 5C). Laubgädem is the only microcatchment which is dominated by RC_2 in the current scenario. This results in a different temporal behavior of peak discharge between the land use scenarios in comparison to Bonegg, Chämleten, and Wallenboden (Fig. 5). This result can furthermore be explained by the fact that flow pathways or channels conducting surface runoff to the river are much shorter and the river is much longer. Thus, surface runoff generated by rainfall event will rapidly reach the stream because it does not have enough time to percolate into deeper soil layers during this very short time.

3.1.4. Wallenboen

Walleboden generates a peak discharge varying between 0.38 and 3.89 $m^3 s^{-1}$ for the current scenario from the 2 to the 300-year return periods. There is a decrease in peak discharge from past to future situation due to the increase in dwarf shrubs of about 20% on the expense of grassland (− 40%) (Fig. 5D). This decrease of peak discharge can be explained by the long flow pathways within this microcatchment as result from the in-situ measurements of flow cross-section reaching 0.7 m^2 giving enough time to surface runoff to infiltrate into deep soil horizons. The flow cross-section of Wallenboden has a higher value in comparison to Chämleten (0.6 m^2) and Laubgädem (0.45 m^2), while Bonegg has the largest flow cross-section (2 m^2). Similarly, while the areas with RC_3 slightly increase, other ones with RC_4 decrease notably (42 to 30%) from the past to the future scenario. The roughness coefficient shows a balancing effect between the surface areas with R_{g5} and R_{g3} (Fig. 6H).

3.1.5. Urseren Valley catchment

The relative difference between the scenarios is smaller when looking at the entire Urseren Valley catchment than when looking only at the microcatchments. Considering the entire Urseren Valley catchment, modelling results show a drastic increase in peak discharge from 55.5 $m^3 s^{-1}$ for the 2-year return period event to 300 $m^3 s^{-1}$ for the 300-year return period event under the current scenario (Fig. 5E). Interestingly, at the catchment scale, the peak discharge for the future scenario is equal or even slightly higher than for the respective current scenarios. Possible reasons are discussed below.

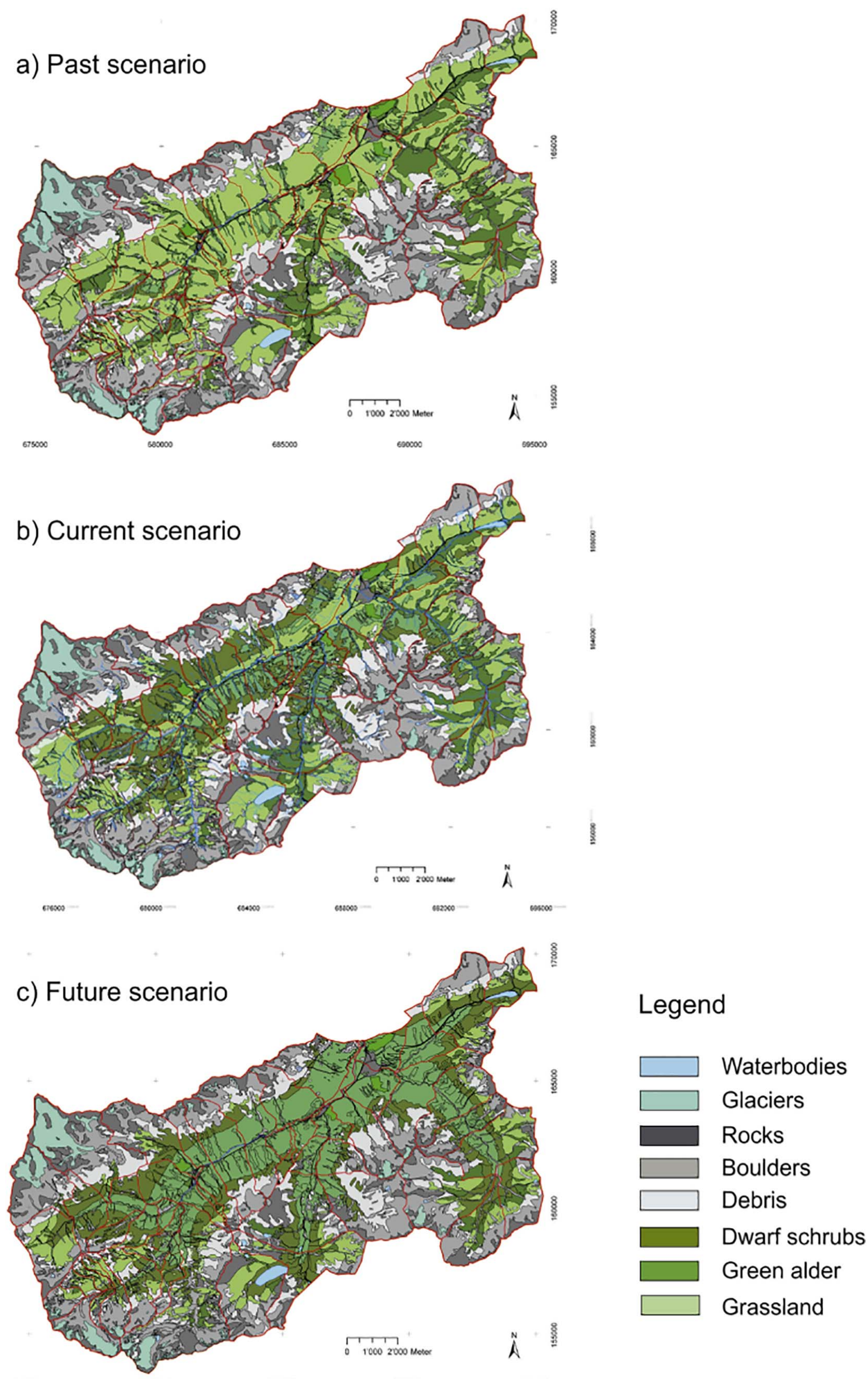

Fig. 3. Spatial distribution of land cover types in the a) past, b) current, and c) future scenarios applied in the ZEMOKOST model for the Urseren Valley catchment.

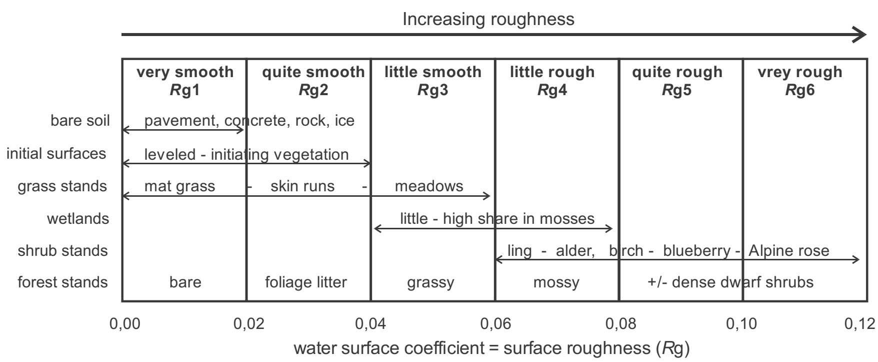

Fig. 4. Roughness coefficient (R_g) of the most important vegetation types used in the modelling (Markart et al., 2011).

3.1.6. Validation

When using consistent scenarios, the model enables reliable estimates of peak discharges in the catchments under consideration. In fact, comparison between the independent statistical method (see Section 2.5.) and simulated peak values according to the ZEMOKOST model showed consistent modelling results for all events except for those with a 2-year return period (Fig. 5E). Indeed, the ZEMOKOST model was calibrated with rainfall events (Kohl and Markart, 2010) whose intensity exceeded that of events with a 2-year return period.

When confronting modelling results with observed values, a peak discharge of about 290 $m^3 s^{-1}$ for a rainfall intensity of 34 mm h^{-1} was calculated for a 100-year return period event with a duration of 4.8 h (Table 3). This value compares consistently to the value observed on 24 to 25 August 1987, when rainfall at an intensity of 40 mm h^{-1} during 10 h resulted in a measured peak discharge of 291 $m^3 s^{-1}$ in the Urseren Valley catchment. The consistency between the observed and the simulated event in terms of intensity, on one hand, and in terms of peak values for 100-year return period events (Fig. 5E), on the other hand, attests the validity of our modelling outcomes.

3.2. Analysis of model-controlling factors

The ZEMOKOST model considers detailed information on vegetation, soil characteristics, and land use as indicators for event *RC* and R_g for surface runoff. At the catchment scale, even though the surface area covered by grassland gradually decreases and the area covered by green alder gradually increases when moving from the current to the future scenarios, the ZEMOKOST model predicted an increase in peak discharge in the Urseren Valley from the 10- to the 300-year return period. At the microcatchment scale, peak discharge changes between the different scenarios depend on the vegetation cover changes, but also of the microcatchment size. Thus, in both Bonegg and Wallenboden, the land cover changes result in high differences in peak discharge due to these catchments' large flow cross-sections (2.0 and 0.7 m^2 for Bonegg and Wallenboden, respectively. Their sizes are also the largest (0.34 km^2 and 0.61 km^2, respectively, Table 1). In Chämleten, the large difference in land cover between the three scenarios has a negligible effect due to the small size of the microcatchment (0.02 km^2) that result in very short concentration time of the flow pathways to the stream. Similarly, the changes in land cover between different scenarios in Laubgädem microcatchment notably affect peak discharge. While the decrease of grassland from 86 to 13% from the past to the current situation (accompanied with a drastic increase of dwarf shrub from 0 to 70%) reduces peak discharge for all events of different return periods, the increase of the area covered by green alder from 4 to 85% from current to future situation results in an increase in peak discharge (e.g., from 0.58 $m^3 s^{-1}$ to 1.04 $m^3 s^{-1}$ for a 100-year period). It appears that dwarf shrub reduces peak discharge more efficiently than green alder. In fact, modelling on plot scale shows that the peak discharges are 0.0148, 0.0147, and 0.0108 $m^3 s^{-1}$ for grassland, green alder and dwarf shrubs, respectively. Furthermore, their concentration times are about 25 min, 45 min and 50 min, respectively for a rainfall event of 100 mm h^{-1} intensity and 1 h duration. Thus, dwarf shrub drastically reduces peak discharge in comparison to grassland and green alder.

The model parameterization (*RC* and R_g, Fig. 6) shows a common pattern for the R_g for all four microcatchments: R_{g3} decreased and R_{g5} increased from the past to the future scenarios. This leads to lower surface runoff. On the other hand, no common pattern could be observed for *RC*; especially the land cover in the Laubgädem catchment is different from the microcatchments Bonegg, Chämleten and Wallenboden (in terms of temporal evolution of dwarf shrubs cover). This suggests that the roughness, based on vegetation classes, mostly affects peak discharge in the investigated catchments.

When looking at the Urseren Valley, the area covered by grassland is smaller, especially in the current and future scenarios, where it amounts to 25 and 12%, respectively. Accordingly, the changed vegetation types play a more dominant role. Although the surface area covered by green alder increases by 38% and the area covered by dwarf shrubs decreases by 26%, from the current to the future scenario, the peak discharge increases. This fact is reflected in the slight increase in RC_5 (Fig. 6I) and the balancing effect between R_{g1} and R_{g3} (Fig. 6J). It appears that the drastic decrease of grassland area from past to current scenario is responsible of the increase of peak discharge. Furthermore, surface area covered by dwarf shrub not only decreases, but also clusters into more continuous zones damping lateral flow (Fig. 3b and c) and resulting in such moderate increase.

It is worth to mention that the areas covered by green alder in the Urseren Valley include also grassland vegetation and explain why *RC* of green alder is comparable to the one of grassland. Whereas, dwarf shrubs include various vegetation types such as birch trees, blueberries, and alpine rose that are denser and cover 100% of the area.

Changes in land use in the Urseren Valley highly impact peak discharge although that 45% of the total catchment area is not favorable for dwarf shrubs growing and therefore not affected by land cover changes but rather by climate changes impact. Future research on the combined effect of land use and climate changes on peak discharge is needed.

4. Discussion

4.1. Model limitations

ZEMOKOST model was developed to simulate storm runoff in alpine catchments (Hemund et al., 2010; Rogger et al., 2012) and can be used to investigate scenarios on land use changes and their impacts on peak discharge (Adams et al., 2010). On one hand, the ZEMOKOST model is suitable for the use in data scarce areas, e.g. alpine environments due to its relatively low complexity and its limitation to only a few relevant parameters. On the other hand, it is a conceptual model and it only includes surface runoff generation parameters and does not consider more complex hydrological processes like evapotranspiration or interception, which might be increased by the expansion of shrubs (FOEN,

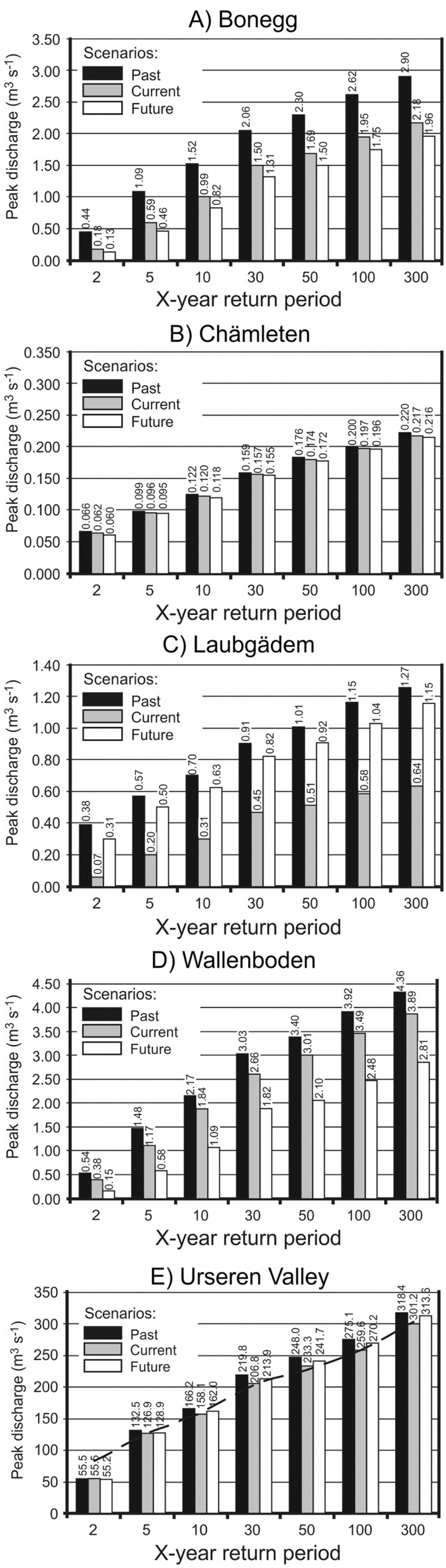

Fig. 5. Modelled peak discharge according to ZEMOKOST for the past, current and future scenarios in A) the Bonegg, B) Chämleten, C) Laubgädem, D) Wallenboden, and E) Urseren Valley.

2012) and have significant impact only for long-term period not considered in this study.

Despite the good performance of hydrological models such as ZEMOKOST to simulate peak discharge under a range of environmental conditions, a number of uncertainties nevertheless remain. One of the main sources of uncertainty in hydrological forecast resides in the choice of the hydrological model to be used. In our case, uncertainties if exist may be inferred to the degree of reliability of the future scenarios that depend, in addition to climate change, of several factors and their complex interactions.

4.2. Land use and land management impacts

The expansion of shrubs is a worldwide issue and the possible hydrological implications of such land cover changes with regard to peak flow during flood events have not been fully investigated to our knowledge.

Literature reviews report that the current land use and land cover changes may provide the key environmental issues in global change (Rogger et al., 2017). For instance, species-rich, traditionally and sustainably used grassland represents an endangered vegetation type of high conservation value across Europe (Klötzli et al., 2010). Many of these grasslands are confined to the Alps and other mountainous regions (Rudmann-Maurer et al., 2008; Homburger and Hofer, 2012). This type of grassland is either under pressure because of agricultural intensification and urban sprawl (Monteiro et al., 2011), or through reduced grazing and mowing and complete land abandonment, commonly followed by colonization by woody taxa in the montane belt (Gellrich and Zimmermann, 2007). The current change in shrubs including green alder across the Alps is much faster than the re-growth of the montane forest (Bühlmann et al., 2016) and is highly related to the socio-economic situation expected to exist in the future that was not accounted for in this study. Recent literature (Caviezel et al., 2017) revealed that the initially described habitat of green alder does not coincide with the recent spreading observed in several studies over the Swiss (Huber and Frehner, 2013; Wiedmer and Senn-Irlet, 2006). It show that green alder is spreading on more gentle slopes and well drained areas, as well as on areas with lower geomorphic activity than anticipated (Caviezel et al., 2017). Thus, the expansion of green alder is much faster and wider than assumed and resulting changes have potentially greater consequences for surface hydrology than expected.

4.3. Climate change impact

While the studies mentioned above have focused on a single driver with regard to peak discharge, a number of multidriver studies have been published recently. While Villarini and Strong (2014) attributed flood changes to rainfall variability changes, Prosdocimi et al. (2015) focused on the dominant role of urbanisation. The physically based catchment model WaSiM-ETH (Water balance Simulation Model) (Schulla, 2012) was applied in the same catchment to simulate the effect of land use changes on total discharge under various soil and climatic conditions and during long-time period (e.g., Alaoui et al., 2014). The authors showed that an increase of 1.3 °C expected to occur in near future would reduce mean yearly discharge of approximately 5% attesting of a relatively higher impact of climate change if compared to the impact of land use alone.

The impact of climate change is highly dependent on other factors. Viglione et al. (2016) reported precipitation change to be the main driver of increasing flood trends in Upper Austria, while they identified land use change as an important driver in small catchments. They

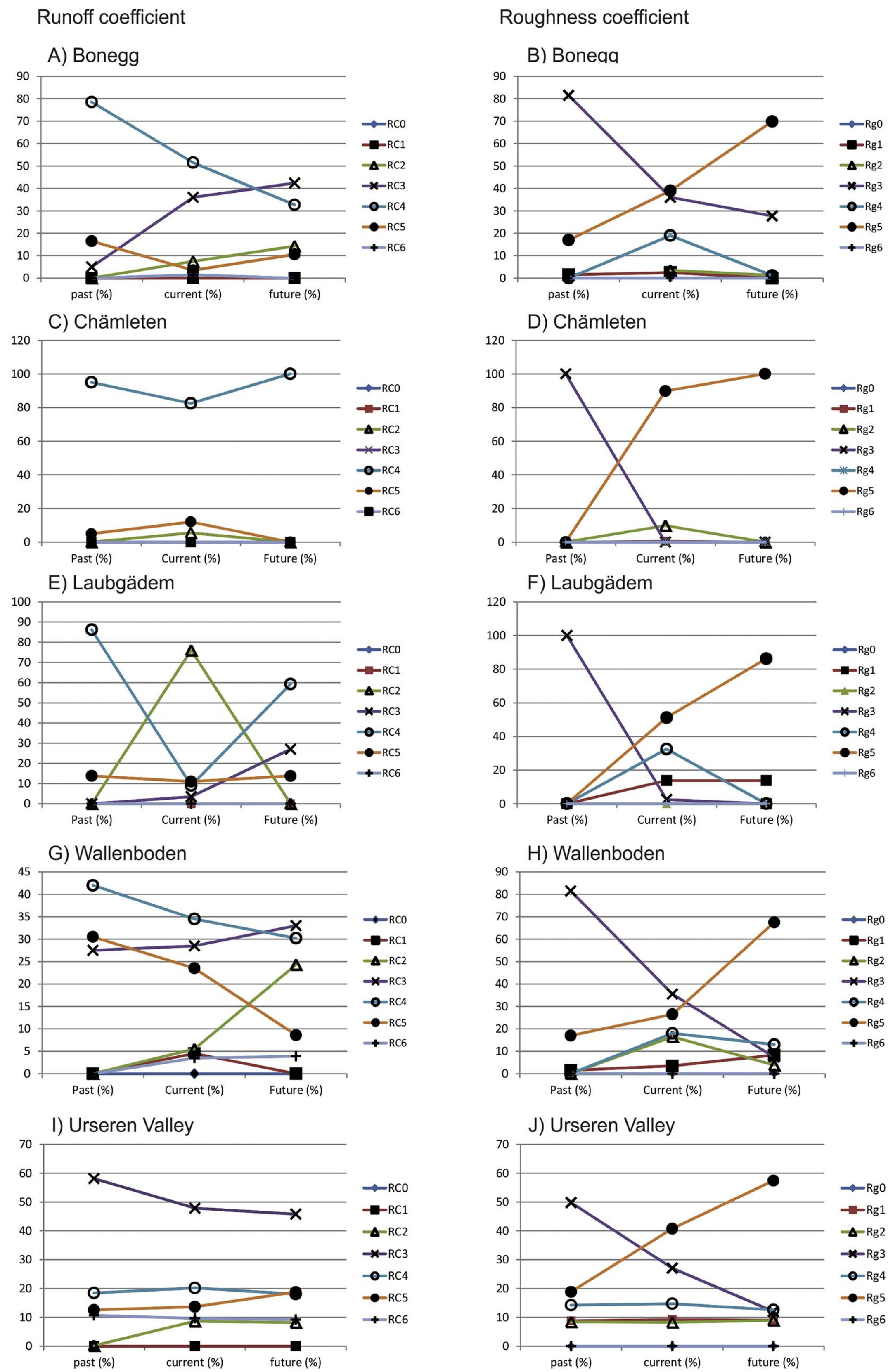

Fig. 6. Changes in the areas (in %) where the classes of runoff coefficient (*RC*) and roughness coefficient (R_g) dominate in the four microcatchments and the Urseren Valley for past, current and future scenarios.

Table 3
Calculated intensities and durations of the events of different return periods according to the ZEMOKOST model.

Parameter							
x-year return period	2	5	10	30	50	100	300
Intensity ($mm\ h^{-1}$)	50.8	52.2	41	34.8	35.3	33.8	35.3
Duration (min)	45	70	120	210	230	290	310

reasoned that the effect of land use change on floods decreases with catchment area due to a shift in runoff generation mechanisms. In small catchments with short response times, floods are mostly generated by high intensity, short duration storms, so the infiltration excess mechanism is dominant. In large catchments with long response times, floods are mostly generated by low intensity, long duration storms, so the saturation excess mechanism is dominant. Thus, climate change will affect peak discharge in many ways.

Climatic changes in the European Alps will increase the frequency of intense precipitation events (Gobiet et al., 2014), which in turn might lead to an increase in surface runoff events during the future snow free periods. All these changes and their interactions create greater uncertainty in the predictions and deserve further consideration. Land use management practices should therefore take into account the hydrological effects of the global changes. Our study provides a basis for assessing this challenging task. Further research is needed to refine the model calibration in order to enhance the reliability of the modelling of short return period (e.g. the 2–5-year return period) especially if both land use and climate changes are considered.

5. Conclusions

The findings of this study lead to the following conclusions:

1. Looking at the microcatchment scale, simulation results indicate that expected changes in the vegetation cover (e.g., increase in the area covered by green alder) will drastically decrease the peak discharge in the future, especially for large microcatchments and for large flow cross-sections, which both leave the vegetation cover considerable time to impact the flow pathways. Considering the entire Urseren Valley catchment, modelling results show a drastic increase in peak discharge for all return periods from 2 to 300 years, with peak discharge ranging from 55.5 to 300 $m^3\ s^{-1}$ under the current scenario. Climate change may further increase these values in the future.
2. At the catchment scale, grassland area decreases from the past to the current scenario, resulting in a decrease in peak discharge. Although the surface area covered by green alder increases and the area covered by dwarf shrubs decreases slightly from the current to the future scenario, the peak discharge increases slightly. This is probably due to the fact that the surface area covered by dwarf shrub not only decreases, but also clusters into more continuous zones, reducing lateral flow.
3. It appears that the roughness coefficient, the flow cross-section, and the length of flow pathways control runoff generation at different scales, and are the critical components of the model. They constitute an important asset when dealing with the impact of land use changes on peak discharge at the catchment scale.
4. This study shows that land management strategies in alpine areas should seek to reduce peak discharge in the future. Further research is needed to consider the combined effect of future land use and climate change on peak discharge in the region.

Acknowledgments

This study was supported by the Swiss National Science Foundation, grant no. CR30I3_124809. The first author would like to thank Bernhard Kohl for his advice on modelling using ZEMOKOST. The authors acknowledge the comments made by two anonymous reviewers which improve the quality of this paper.

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